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Underwater geothermal exploration – diving into the deep

Maren Brehme and Anna Jentsch

Geothermal Energy and Geofluids Group, Department of Earth Sciences, ETH Zurich, Switzerland

mbrehme@ethz.ch, ajentsch@ethz.ch

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ABSTRACT

Worldwide, there is a large amount of untapped geothermal resources located either offshore or onshore under lakes. To investigate the possibility of exploiting these geothermal resources, exploration techniques need to be adapted to certain requirements. This is because the same methods used on land simply do not work underwater. During exploration, the focus is on finding fluids and fluid pathways. Fluid pathways or structural features such as faults, pockmarks, hot springs, or fluid seeps, can usually be located underwater by indirect methods, such as bathymetric measurements or seismic surveys. However, detailed mapping and sampling of the seafloor or lake bottom requires more refined technologies.

For our studies, we built an underwater field laboratory that combines structural and geochemical methods to explore underwater geothermal resources. We use bathymetry to locate fluid pathways and a remotely operated underwater vehicle (ROV) equipped with an underwater GPS system for mapping and sampling points of interest. The ROV can collect samples for fluid and sediment analyses using a fluid or sediment sampler mounted on the drone. It records physicochemical parameters such as salinity and water temperature, while also taking high-resolution videos and photos. This makes otherwise inaccessible or hard-to-reach areas visible. The use of rugged materials in manufacturing the ROV allows it to operate in extreme environments with higher temperatures and low pH levels. Red laser beams at the front of the ROV enable underwater distance measurements to estimate the size of e.g., springs or fractures.

In 2023, three field campaigns were conducted at three lakes with different scientific objectives to test and evaluate the functionality of this unique lab for underwater exploration. We describe the different lakes (Lake Zurich and Lake Cadagno, Switzerland and Lake Ranau, Indonesia) in terms of their geological context and lake characteristics, the workflow adapted to the research question, to finally summarize the limitations and opportunities of ROVs in geothermal exploration campaigns.

1. INTRODUCTION

Geothermal exploration involves to a large degree fieldwork. It is an established and inevitable approach for obtaining data in unknown regions. However, regions still overlooked are areas beneath the water, e.g. lakes, rivers, and oceans. They can cover significant areas of a geothermal resource and therefore should be considered during geothermal exploration studies.

Brehme et al. (2019 and 2021) located geothermal sweetspots in volcanic lakes. More precisely, the most productive wells of the Lahendong geothermal field target the resource right beneath the lake. Also, in Central Anatolia, the hottest geothermal well of Turkey was drilled near a volcanic lake. Both studies showed the correlation between fluid pathways mapped onshore and offshore and their relation to the geothermal resource. In fact, lake bottoms reveal structures, such as faults, fractures or springs, much better than earth's surface, due to less coverage by vegetation and less exposure to alteration processes. This shows the large potential of mapping studies in water bodies.

With that purpose, we built a field-laboratory, specialized on underwater exploration campaigns. The field-laboratory is transportable and consists of different equipment. An echosounder to map the lake floor topography enabling the identification of faults, fractures or holes. Another instrument is the remotely operated underwater vehicle (ROV), equipped with an underwater GPS system. The ROV can collect samples for fluid and sediment analysis, record physicochemical parameters, while recording video or taking pictures. Samples are further treated onsite and prepared for detailed analysis in the onshore laboratory. For practicality, the field-laboratory is designed to be run by small teams or even a single person. This simplifies fieldwork in terms of manpower, transportation, custom handling and costs in general.

The existing field laboratory was used during three field campaigns in 2023 in Indonesia and two sites in Switzerland. The study areas represent different possible locations of operation. A volcanic lake with geothermal potential close to an active faulting system and several volcanoes, a glacial lake with pockmarks and fault structures, and a lake with geobiochemical stratification and subsea springs. The maximum depth range of the lakes is between 20 and 220 m.

2. UNDERWATER GEOTHERMAL EXPLORATION - THE FIELD LABORATORY

2.1 Bathymetry

For bathymetry, different instruments were used. The best equipped is a Lowrance Elite TI 7 from Navico with a CHIRP (Compressed High Intensity Radar Pulse) sonar, GPS navigation and a multibeam echosounder with side-scan and down-scan imaging (Fig. 1). The down-scan detects the depth at a single point and the side-scan captures information and views at each side of the boat. This allows for visualizing subsurface structures and points of interest.

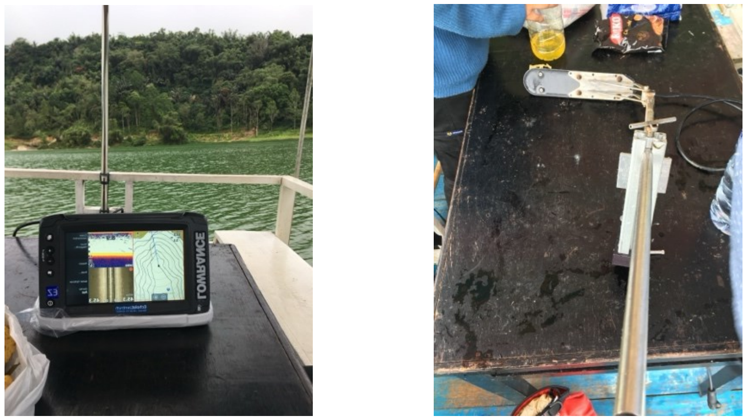

Figure 1: Lowrance Elite TI 7 bathymetry instrument with screen for live data view and the bathymetry transducer

A very practical and quick way to measure depth data from lakes is a "sonar ball" from the company Deeper (Fig. 2). The Deeper Sonar CHIRP+2 is originally designed for fishing, but we were able to show that this very light and small device is able to provide the same quality of data as the one from Navico. With integrated GPS and a chirp with three frequencies (100, 240 and 675 kHz), it has an internal battery with a runtime of up to 15 hours and is the size of a tennis ball. This makes it easy to transport and enables quick exploration of smaller lakes with instant data transfer via a Wi-Fi connection to the corresponding Fish Deeper App.

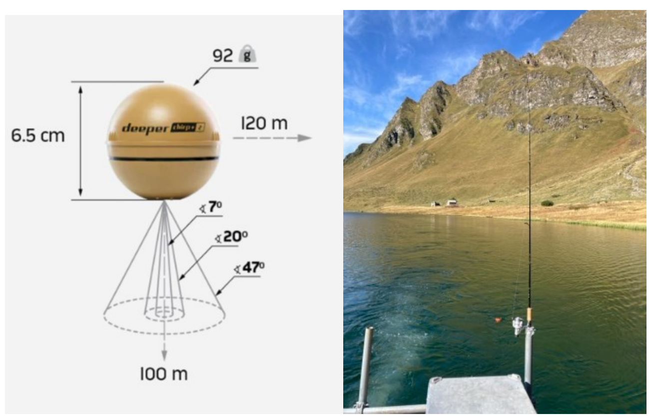

Figure 2: Deeper Sonar CHIRP+2 and technical specifications about its depth, size, weight, and connection range and b) deployment of the sonar on a fishing rod at Lago Cadagno.

2.2 The ROV and GPS

The remotely operated underwater vehicle (ROV) is a Qysea Fifish V6 Plus drone that weighs 5 kg and can dive up to 150 meters deep (Fig. 3). It has a size of 383x331x158 cm. The drone is equipped with a cable for data transfer at all times and steered with a controller with joysticks and small wheels. It also includes a virtual reality application that allows the user to see and steer the ROVs' diving direction through goggles. It can move in all directions: 360° rotation, lateral and tilt. In addition, the drone has a variety of functions such as distance and altitude sensors with respective lock functions and a motor stabilization system to avoid obstacles and to fix distances. It also has a laser scaler to measure objects. The drone has LED lights with up to 6000 lumens and a camera with 4k ultra-high-definition resolution for photo and video recordings. Different instruments can be mounted to the ROV, such as liquid and solid samplers, a shovel, gripping pliers, or a salinity sensor. Its robust materials allow it to operate in extreme temperature and acidity conditions.

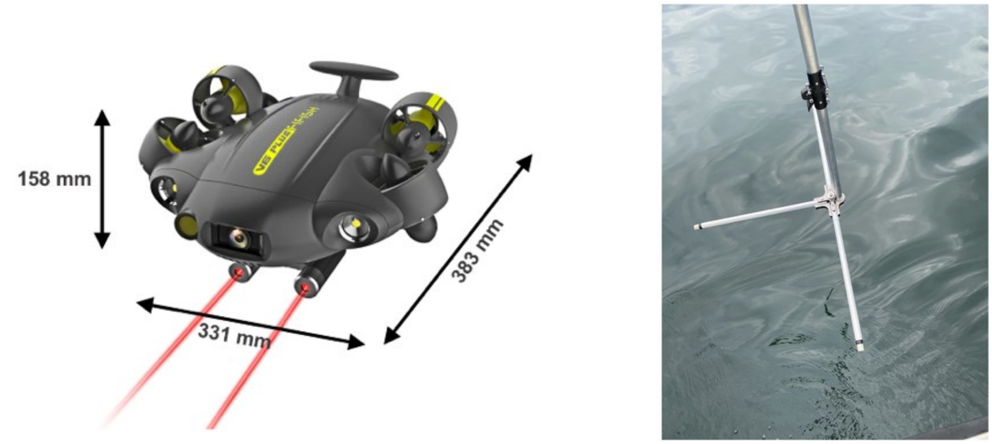

Figure 3: Left: Image of the Fifish drone (modified from OnTheGo, 2022), Right: Antenna for the underwater GPS System

The drone has an underwater rapid positioning system (U-QPS) from the Norwegian company Water Linked with ultra-short baseline navigation, integrated GPS and an inertial measurement unit (IMU), which is used to calculate the absolute coordinates. Acoustic signals are sent from the tracking device on the ROV to an antenna attached to a boat or onshore.

Before purchasing, we compared different underwater drones and GPS systems. We decided on the Qysea Fifish V6 Plus drone because of its small size, easy handling, high quality manufacturing, and the best combination of installable equipment, diving depth and battery capacity.

2.3 Sampling

Water samples taken from different depths in the lake/river/ocean are brought to the surface by the drone. Here, physicochemical parameters are measured, e.g. temperature (T), electrical conductivity (EC), pH, total hardness (TH) and carbonate hardness (CH). We use probes from WTW (Wissenschaftlich-Technische Werkstaetten GmbH). Total and carbonate hardness were measured using portable field kits and titration from Merck. The water samples were collected in clean polyethylene bottles, each thoroughly rinsed three times with water to be sampled. At each sample point, two 50 mL samples were filtered using 0.45 µm cellulose-acetate filter paper. For cation analyses, samples were acidified with HCl for preservation of samples. Samples are then brought to the laboratory for detailed analysis on cation and anion concentrations.

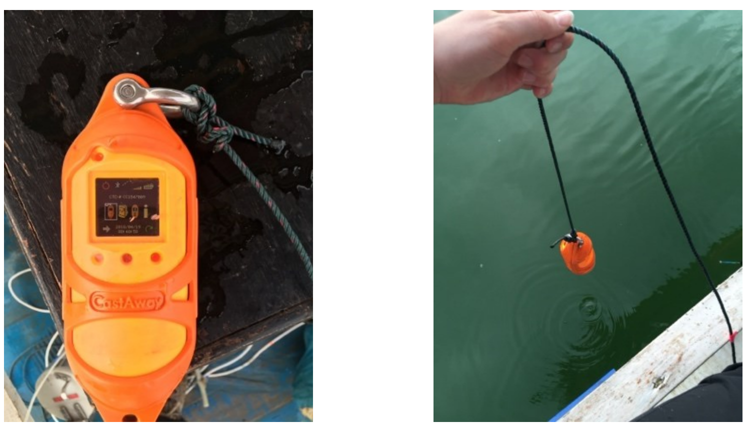

Figure 4: CTD logger with sensor for electrical conductivity, density, temperature, pressure and sonic velocity is lowered into the water on a rope.

Physicochemical profiles have been logged using the CastAway-CTD logger from SonTek (Fig. 4). The logger includes sensors for conductivity, density, temperature, pressure and GPS. It allows sampling at a 5 Hz sampling rate up to 100 m depth, translated to 15 cm sampling distance.

3. FIELD APPLICATIONS

3.1 Switzerland

Two lakes were studied in Switzerland using the new field laboratory: Lake Zurich and Lake Cadagno.

3.1.1 Lake Zurich

This study is part of the BSc thesis from Alexandra Aregger, conducted in April 2023 (Aregger, 2023). The perialpine Lake Zurich is set in the foreland of the Swiss Alps. The lake is elongated in the NW-SE direction with a lake surface level at 406 m asl and a surface area of 88.7 km2 (Fig. 5 left, Swisstopo, 2014). The lake is divided by a moraine into the Untersee to the north and the Obersee to the south. It is up to 136 m deep and inflow of water is through three large rivers Linth, Jona and Waegitaler Aa in the south. The Limmat River is the lakes' outflow located in the city center of Zurich in the north. The lake shape was formed by the Linth Glacier, which carved the U-shaped trough of Lake Zurich into the Upper Freshwater Molasse. During the glacial retreat, clayey sediments were deposited in an undulating way, followed by plastic mud filling up the depressions and smoothing the lake floor. These sediments have a thickness of up to a hundred meters and more with possible areas of iceberg sediments Schindler (1976).

In these sediments, pockmarks have been discovered in a nearly perfect circular structure. Pockmarks are concave, crater-like depressions at the bottom of lakes or the ocean and related to subsurface fluid flow, including gas (King & MacLean, 1970). The objective of studying Lake Zurich was to investigate the origin and activity of the pockmarks. The field laboratory was used to study the morphology of the pockmarks (distribution, structure, diameter and depth) as well as to take images and videos of the pockmark sites with the underwater drone. Additionally, sediment cores were taken to study the activity of the pockmarks via the difference in the sedimentation in- and outside of the pockmarks.

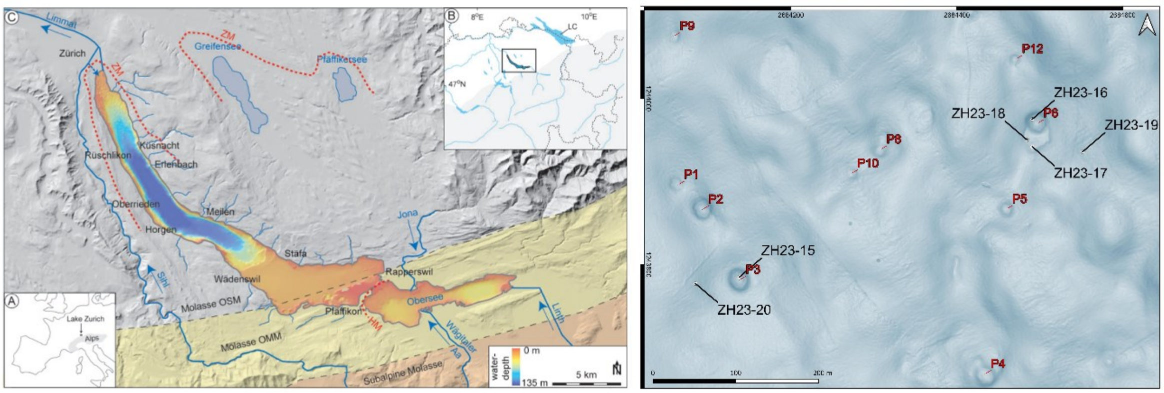

Figure 5: Left: Map of Lake Zurich (Strasser, 2008). The insets A and B show the geographic location in Europe, respectively in Switzerland. In C, the bathymetry map of Lake Zurich is shown, marked with all water inflows and outflow. The geological setting of the molasse and the moraines (dashed red lines) overlies the digital elevation map from the area. Right: Coring locations in and around pockmark P3 and P6.

Fourteen pockmarks were mapped in the bathymetric dataset, with a diameter of 15 to 45 m, a depth ranging between 0.6 to 2.0 m and slopes of up to 19° steep (Fig. 5 right). The pockmarks are all located within an area of 0.8 km2. The preservation of 37.5 cm thick laminated sediments proves that the pockmarks were not active during the last hundred years since the start of the eutrophication. No gas bubbles were recorded with the camera from the ROV at any of the pockmark sites. The ROV survey inside the pockmarks revealed an uneven lake bottom with little hole-like depressions. Most of the time, objects were found to be lying inside these structures (such as dead plants and a bucket). A several-meter-long notch was observed 10 cm deep into the sediment (Fig. 6). The measured water temperature at the lake ground was 6°C.

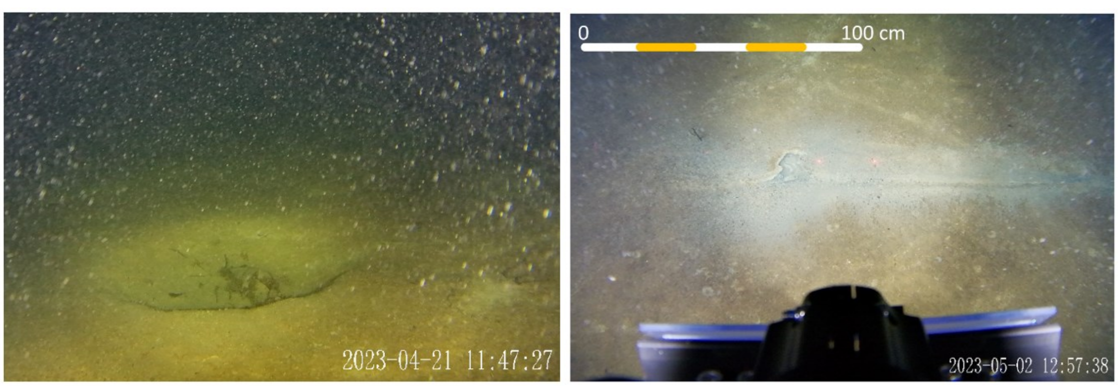

Figure 6: Left: Circular depression (~1m) with a dead plant. Right: A roughly 120 cm long white stripe. The sediment looks enriched in shale fragments.

The results lead to the theory that the pockmarks of Lake Zurich are relic structures of past fluid flow. It is unknown when they started to become active and for how long they were active. The fluid might have consisted of gas from decomposed organic matter derived from the iron sulfide mud layer which was deposited in the Boelling interstadial. It is still questionable, why they only occur within a small part of the lake. Additionally, it might be possible that gas or water from bigger depths was responsible for their formation.

3.1.2 Lake Cadagno

This study is part of the MSc thesis of Céline Graber, conducted end of August 2023 (Graber, 2024). Lago Cadagno is located in the southern Alpine region in Val Piora 1921 m above sea level (Fig. 7). The lake is small with an area of 0.26 km2 and a maximum depth of 21 meters (Del Don et al., 2001). Its formation is based on glacial erosion during the last glacial period 12'500 years ago (Stapfer, 1991; Wirth et al., 2013). The northern part of the lake lies in pre-Triassic gneisses and mica schists. A dolomite vein with gypsum deposits folded in the Piora synclinal crosses the southern lake bank. Lago Cadagno is a rare example of a crenogenic meromictic lake. The lake water is permanently stratified, creating a partially anoxic environment in the lowest layers. At a depth of 10-14 meters, there is a permanent chemocline, which harbors a dense population of phototrophic sulfur bacteria (Del Don et al., 2001; Tonolla et al., 2003). It separates high-density salt-rich water from the electrolyte-poor, low-density surface water. The deep water is fed by subaquatic springs. These originate from the complex karstic system that penetrates the gypseous dolomite vein (Del Don et al., 2001). The source of this spring water is located about 2 km southeast in the Calderoni Sinkhole, as trace experiments have shown (Otz et al., 2003).

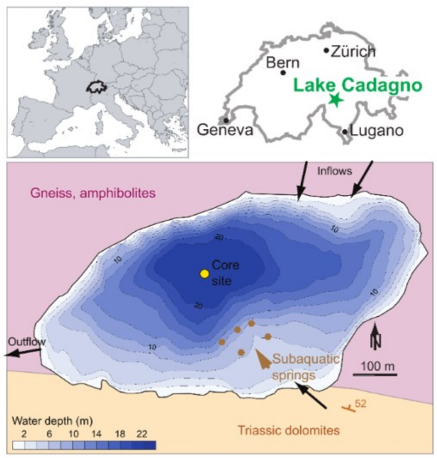

Figure 7: Location and bathymetric map of Lago Cadagno in southern Switzerland (modified from Zander et al., 2023)

Information on the distribution, shape and appearance of the subaqueous springs is still scarce. The water of the Mixolimnion corresponds to the surface runoff of a drainage area of about 2 km^2 to the north of the lake. The underlying crystalline rocks are rather resistant to chemical weathering, which explains the deep ionic strength and oligo- to mesotrophic water in the mixolimnion (Del Don et al., 2001). The monimolimnion is characterized by a constant supply of sulphate, carbonate, calcium and magnesium ions from the subaquatic sources (Del Don et al., 2001). Carbonate acts as a buffer and keeps the pH value of the monimolimnion constant at 7 (Del Don et al., 2001). The sulphate that enters the monimolimnion through the subaqueous sources is used as an electron acceptor for anaerobic respiration, resulting in a high concentration of hydrogen sulfide.

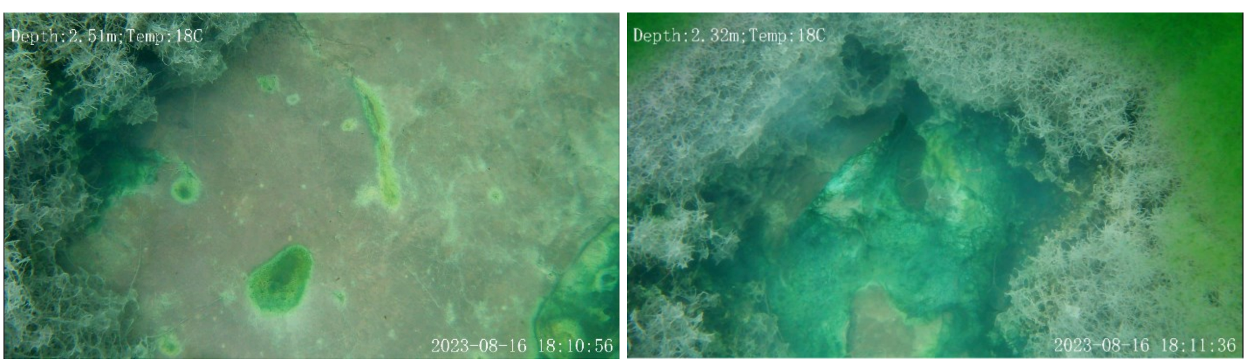

Figure 8: Structures that could be the source of the spring water. The photograph on the right shows the white discoloration of the macrophytes surrounding the springs.

We discovered a large number of springs and recorded them with the help of photos and video footage (Fig. 8). In sunny weather conditions, the springs could even be located from the surface thanks to the milky fluid film and the white discoloration of the macrophytes. In the spring areas demarcated by the macrophytes, there are various structures such as discolored openings and white patches in the ground or chimney-like structures of various sizes, which could be possible spring outlets. The spring water appears to have multiple outlets that collectively form a spring area. The shape of the springs is very heterogeneous, although most were elongated structures with different channels that vary in width and length from dm to m in size and often have a funnel shape. After heavy rainfall, changes in the springs were observed on the second day. The fog of milky fluids seemed much denser and visibility was generally poorer. The under-water current seemed to be much stronger, which made it more difficult to control the ROV. Water samples from springs at different depths (3-18m) and CTD-depth profiles show a strong difference in salinity, temperature, Cl, SO4 and K-concentration. The shallower springs have higher ion concentrations, total salinity and higher temperatures.

3.2 Indonesia

The fieldwork in Indonesia took place in June 2023 in the volcanic-geothermal system of Lake Ranau on Sumatra, where warm and hot springs on the lake shore are the most obvious signs of geothermal activity in the subsurface. Lake Ranau is a large Pleistocene caldera located on the Sumatran Fault Zone (SFZ) and is bounded in the southeastern part by Mount Seminung, a Holocene stratovolcano, under which part of the geothermal system is thought to be situated (Hochstein, 1993). The age, location, and size of the caldera make it a promising site for further investigation of its geothermal resource. However, in the immediate vicinity of Mount Seminung, there are no geomorphologic expressions of the large SFZ, which normally has a prominent fault trace across the island striking northwest-southeast (Fig. 9). Only in the south of Mount Seminung is evidence of a fault trace, while the other faults were determined by thermal manifestations, geomorphological studies, gravity, and resistivity measurements. Due to the young volcanism, the active faults are covered by abundant volcanic deposits. So far there are no temperature gradient or exploration wells, so the classification as a medium enthalpy geothermal system is based solely on Na-K geothermometers, which give temperatures between 200-220°C (Afiat et al., 2021). As only onshore exploration work has been carried out so far, the aim of this study was to combine a bathymetric survey with geochemical data from onshore and offshore sites to characterize the geothermal system, its potential extension under the lake and the identification of hidden structures at the lake floor. This survey was a collaboration with PLN, the national electricity provider, that holds the exploration license for this area and is particularly reliant on underwater exploration support to find a suitable location for the first exploration well.

As the Ranau caldera covers a large area of 15 x 8 km, we focused the bathymetric survey on the most interesting areas, i.e. areas with known fish deaths documented in the last 50 years, areas where the SFZ is suspected to cross the lake, and areas corresponding to the location of thermal manifestations on land. Care was taken to ensure that routes were in most cases no more than 300 metres apart to achieve good resolution. In total, we covered 428 km, measured 29 CTD profiles and collected samples for major ion concentrations and physicochemical parameters at 17 sites. Data processing and analysis are still ongoing, so the results presented below and their interpretation are preliminary.

A maximum depth of 220 m was measured, which in some places was already reached within 400 m of the lake shore. In particular, the north-western part of the caldera has very steep slopes, which is expected due to the high topography of the area and is typical of a caldera rim. We have found evidence in our bathymetry data that the SFZ is leaving traces to the south-east and north-west of the shoreline. However, further processing of the data is required before a final conclusion can be drawn. It was particularly challenging to get good underwater footage as we could not anchor (due to the depth of the lake) and the boat was almost always affected by a strong drift. There were also strong underwater currents, which meant that we could only get good footage in places where we could tie up to rock formations or trees, i.e. on the lake shore. This limited our underwater research activities with the ROV and we often did not dive to the sites we were interested in. Because of the maximum sampling depth of 100 m by the CTD logger used here, we have no information from the deeper parts of the lake. However, CTD profiles in the vicinity of thermal manifestations on land (< 1 km) show conductivity and temperature fluctuations in the water column. Lake Ranau is classified as a meromictic lake with an oxygen-depleted depth between 70 and 100 m and the simultaneous occurrence of high concentration of hydrogen sulphate. This indicates the possible input of magmatic/hydrothermal discharges into the lake through permeable pathways. The water analysis from warm-hot springs and lake water has shown that most waters are of bicarbonate origin with some volcanic contribution of deeper waters. Electrical conductivity values range between 500 to 1600 µS/cm, pH values range from 6.3 to 7.5, and temperatures range from 35 to 58°C.

Overall, Lake Ranau presented a unique but also challenging field site for the ROV where new ideas and improvements have been stimulated. It is important to understand that ROVs with the size and weight of the Qysea Fifish are difficult to operate in open and deep areas of large lakes, especially if the points of interest are, for example, small hydrothermal vents or large faults. In both cases it requires systematic scanning of the lake floor in order to recognize/record changes in the morphology. Still, the ROV is very helpful in taking samples of fluids from different depths as well as sediment samples. The evaluation of the data is ongoing and will be published in the near future, but preliminary results indicate the continuation of the geothermal system beneath the lake.

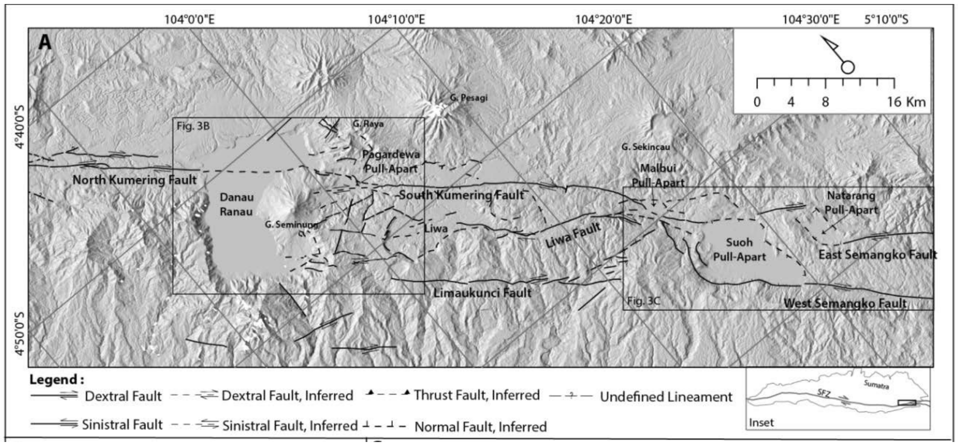

Figure 9: Structural map of the area northwest and southeast of Lake Ranau illustrating known and inferred fault segments. The Kumering and Semangko faults are segments of the great Sumatra Fault Zone (SFZ). Inset shows the location of the study area on Sumatra Island and the SFZ (modified from Aribowo, 2018).

Figure 10: Image of the north-western slope at a depth of 57 m, showing no signs of biogenic activity. Only a thin layer of unconsolidated material (mixture of fine sediments and dead organic matter) is deposited on solid rock.

4. CONCLUSIONS

After operating the field laboratory three times in 2023, the test of the underwater drone showed how simple and quick field investigations can be carried out. With the maneuverable ROV Qysea Fifish V6 Plus, which travels at a speed of up to 1.5 m/s, the lake floor was reached within a few minutes (depending on the depth of the lake), and images, videos, and measurements could be taken immediately. Maneuvering the ROV proved to be easy to learn as there are three different dive modes that are pre-programmed and can be changed by a switch on the remote control. The distance lock function helps the ROV to maneuver at the desired diving depth without colliding with the lake floor and stirring up unconsolidated sediment, as long as there are no strong currents in the lake. The camera and lighting worked perfectly, allowing high-resolution images to be taken even at a depth of 90 metres (the maximum diving depth reached so far). All of the ROV's sensors as well as the additional add-ons, such as the fluid sampler, worked perfectly in most cases.

Major improvements compared to classical field investigations are:

• The combination of ROV and GPS allows to exactly sample the points of interest, compared to before when a water sampler was lowered and meanwhile the boat drifted away from the point of interest.

• The field laboratory is usable by smaller teams of 2-3 people.

• It is lightweight and can be transported depending on the needs in 1 to 2 boxes.

• The battery of the ROV does not exceed 155 Wh and it is therefore permitted to transport the ROV in hand luggage while flying

• Thanks to the real-time transmission of video recordings, the examination area can also be adjusted spontaneously if areas of interest are identified.

• The 200 m long data transmission line also enables operation from land and can be further extended to 300 m.

Challenges included:

• Rough weather conditions, e.g. cold temperatures, storms, rain but also strong sunlight made it difficult to control the ROV and see the screens.

• Due to the strong underwater currents, it was a challenge to control the ROV, even when it was in location lock mode. This made it difficult to approach sources without damaging them or drifting away. Additionally, sampling just a few centimetres above the lake floor was problematic due to the risk of crashing into it.

• The filled fluid sampler disturbs the ROV's balance, which means that the additional weight at the front tended to keep it on a constant incline. In combination with the strong current and the short distance to the bottom of the lake, this caused the snout of the fluid sampler to poke into the bottom of the lake.

• Underwater plants get sucked into the motors of the ROV and block them such that the ROV is not able to maneuver anymore and has to be pulled out with the cable

• The internal battery can last up to 2 hours but only if diving depths are not too deep, the lights and add-ons are not needed all the time and no additional challenges e.g. currents, occur. Otherwise battery will be empty quite fast and an additional power supply is highly recommended.

• The Deeper Sonar CHIRP+2 can only be used at a maximum speed of 3 km/h, otherwise it will not record any data as the ball is very light and bounces when traveling faster

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