Bathymetry and Geochemical Profiles as New Mapping Tools for Fault Permeability

Maren Brehme[1], Ronny Giese[1], Lily Suherlina[1], Yustin Kamah[2]

[1] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Geoenergy, Telegrafenberg, 14473 Potsdam, Germany

[2] UpstreamTechnology Center Pertamina, Jl. MedanMerdeka Timur no. 6, Jakarta, Indonesia

brehme@gfz-potsdam.de

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ABSTRACT

To locate and characterize faults is an important step towards understanding geothermal systems.

Our novel approach, presented here, uses bathymetry and geochemical profiles to map hidden geothermal structures in a volcanic lake. The lake in the Lahendong geothermal field has light to dark greenish acidic water (pH3) and a size of 800x600 m. Previous studies show, that the lake masks geothermal features e.g. faults and fumaroles.

Our study resulted in a 3D bathymetry showing a total depth of 0.5 to 35 m. In general, the northern and eastern part of the lake is shallower with 8-10 m at maximum. The southern and western part is much steeper and shows hole structures with depths of 22-35 m. Holes at the lake bottom can be clearly related to faults and their intersection points. Additionally, geochemical profiles in the lake indicate inflow zones of saline, hot acidic water into the lake at certain locations.

Combining bathymetry and geochemistry we were able to create a detailed fault map of the area.

1. INTRODUCTION

Faults, fractures and geothermal features, i.e. hot springs or fumaroles, give key information on the subsurface. To locate and characterize these structures is an important step towards understanding and commercially using the subsurface, e.g. for geothermal energy. However, these structures can be hidden by erosion, soil, vegetation, lakes, rivers or calderas and are then difficult to spot and map. Therefore, there is a strong need to develop tools to identify and map hidden structures.

Until now, faults have been explored using a combination of geophysical measurements (Harinarayana et al., 2006; Garg et al., 2007) and structural geological mapping (Faulds et al., 2010). If faults are not visible in the field, hot springs, gas emanations and their alignments give hints for their locations (Lynne, 2013, Aubert and Baubron, 1988; Voltattorni et al., 2010). However, these approaches are limited to structures which are evident at the surface. Bathymetry has mainly been used to estimate volume changes of volcanic lakes combined with detection of volcanic activities and risk monitoring (Hurst and Dibble, 1981; Bailey, 1989; Bernard et al., 2004; Takano et al., 2004; Coolbaugh et al., 2007; Anzidei et al., 2008; de Ronde et al., 2015).

Our approach, presented here, uses bathymetry and geochemical profiles to identify and characterize geothermal structures hidden by a lake above a geothermal reservoir.

2. STUDY AREA AND STRUCTURAL-GEOLOGICAL SETTING

Our first test site is the caldera lake Linau in the Lahendong geothermal field in North-Sulawesi, Indonesia. Neumann van Padang (1951) states an average depth of 10-12 m for the lake. Previous studies show, that the lake masks faults and fumaroles (Brehme et al., 2016; internal communication). In general, the area is characterized by a complicated structural-geological setting with different phases of faulting and fracturing (Brehme et al., 2014; Brehme et al., 2016). The strongly compartmentalized geothermal system currently produces 80 MWe from ten production wells at 1500-1800 m depth.

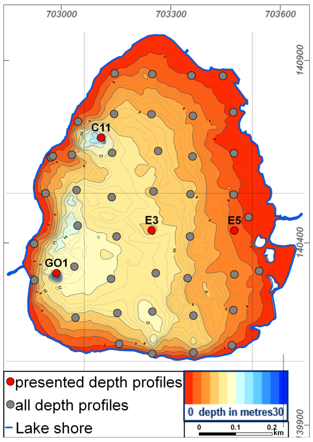

Figure 1: Bathymetry depth map of Lake Linau and geochemical measurement locations

3. METHODS

A Lowrance Elite TI 7 from Navico installed on a raft measured the bathymetry driving in circles with decreasing diameter on the lake.

Conductivity, density, temperature and pressure profiles have been logged using the CastAway-CTD logger from SonTek.

4. RESULTS

The main result of the survey is the detection of 22-35 m deep holes at the lake bottom. They are aligned at the western shore along a NE-SW trending line. The holes have a diameter of 20-40 m at the top and 4 m at the bottom. Other parts are 14 m deep in the west and 12 m deep in the south of the lake. In general, the northern and eastern part of the lake is shallower with 8-10 m at maximum (Fig.1 and Fig.2).

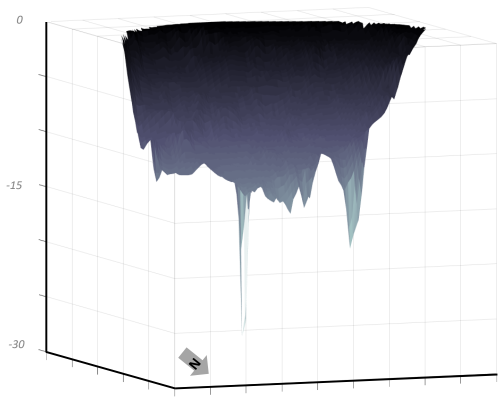

Figure 2: 3D bathymetry of Lake Linau, view from NE towards lake surface

Geochemical measurements were taken along a systematic grid with 100 m distance between the measurement points (Fig.1). Here, we present measurements from the deep holes in the west (G01) and northwest (C11), an average profile in the middle of the lake (E3) and a measurement in the eastern shallow area (E5) (Fig.3).

All profiles show a strong decrease in temperature in 5 m depth and a moderate decrease in 15 m depth (Fig.3). The temperature pattern increases below 15 m but gets unstable. Temperature peaks in the deep hole G01 show inflow zones of warmer water.

Electrical conductivity generally decreases to a minimum above 5 m depth. Between 5 and 15 m it slightly increases or is stable. Below 15 m, conductivity is much more unstable but shows parallel peaks to the temperature pattern. Hence, the warm inflowing water is highly saline.

pH has been measured at points over depth. The most neutral pH (5.6) is in the east at E5. In the lake middle and at C11 pH is increasing over depth. This behaviour is related to an inflow from hot springs into the lake at shallow depth. The decrease in pH in the deep hole G01, shows that the warm, saline water inflows at depth are acidic.

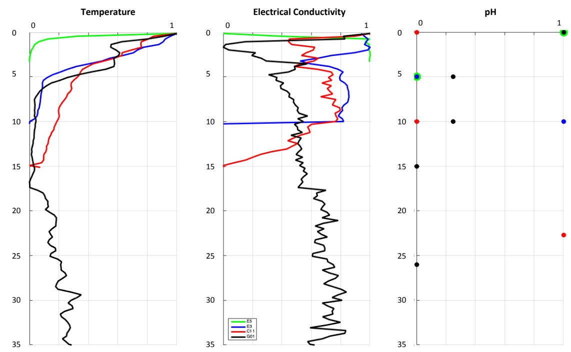

Figure 3: Normalized geochemical depth profiles from selected locations in Lake Linau

5. OUTLOOK

Combining bathymetry and geochemical measurements is a successful approach to characterize hidden structures beneath lakes. Bathymetry uncovered deep hole structures, which can be clearly related to faults. Faults in the lake area were newly discovered or confirmed. The 3D view shows that faults exactly intersect where the bathymetry shows deep depressions in the lake or where manifestations occur onshore (Fig.5 right and Fig.6):

A previously known strike-slip fault (SS1) intersects the lake in the west and cuts the deep hole (C11). The other deep hole (G01) is at the crosspoint of a normal fault (N2) striking N-S intersects and a newly discovered fault (F1) striking NW-SE.

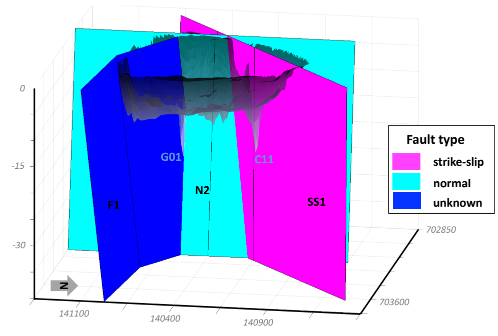

Figure 5: 3D bathymetry with fault locations, types and intersection points

Additionally to mapping of faults, its role in conducting fluids is important to understand. Deep inflow of hot saline water at fault intersections were confirmed by the location of hot springs (M10, M15, M16). Furthermore, geothermal well data show the highest productivities (LHD 23, LHD28) at fault intersections. Another highly productive area, not targeted yet, is expected near to the deep hole G01.

Bathymetric data linked with geochemical measurements is a successful mapping tool for hidden structures in a lake. The approach allows to develop a conceptual geological 3D model of the subsurface. This technique is not limited to geothermal reservoir characterization but has a wide applicability for subsurface utilization, e.g. conventional reservoirs, structural geological mapping or subsurface waste storage.

REFERENCES

Anzidei, M., Carapezza, M.L., Esposito, A., Giordano, G., Lelli, M., and Tarchini, L., 2008, The Albano Maar Lake high resolution bathymetry and dissolved CO2budget (Colli Albani volcano, Italy): Constrains to hazard evaluation: Journal of Volcanology and Geothermal Research, v. 171, no. 3–4, p. 258–268, doi: 10.1016/j.jvolgeores.2007.11.024.

Aubert, M., and Baubron, J.C., 1988, Identification of a hidden thermal fissure in a volcanic terrain using a combination of hydrothermal convection indicators and soil-atmosphere analysis: Journal of Volcanology and Geothermal Research, v. 35, no. 3, p. 217–225, doi: 10.1016/0377-0273(88)90018-2.

Bailey, R., 1989, Geologic Map of Long Valley Caldera , Mono-Inyo Craters Volcanic Chain , and Vicinity , Eastern California: USGS Professional paper, p. 11.

Bernard, A., Escobar, C.D., Mazot, A., and Gutiérrez, R.E., 2004, The acid volcanic lake of Santa Ana volcano, El Salvador, in Special Paper 375: Natural Hazards in El Salvador, p. 121–134.

Brehme, M., Blöcher, G., Cacace, M., Kamah, Y., Sauter, M., and Zimmermann, G., 2016, Permeability distribution in the Lahendong geothermal field: A blind fault captured by thermal–hydraulic simulation: Environmental Earth Sciences, v. 75, no. 14, doi: 10.1007/s12665-016-5878-9.

Brehme, M., Moeck, I., Kamah, Y., Zimmermann, G., and Sauter, M., 2014, A hydrotectonic model of a geothermal reservoir - A study in Lahendong, Indonesia: Geothermics, v. 51, doi: 10.1016/j.geothermics.2014.01.010.

Coolbaugh, M.F., Faulds, J.E., Kratt, C., Oppliger, G.L., Sheveneil, L., Calvin, W., Ehni, W.J., and Zehner, R.E., 2007, Geothermal Potential of the Pyramid Lake Paiute Reservation, Nevada, USA: Evidence of Previously Unrecognized Moderate-Temperature (150-170°C) Geothermal Systems Mark: GRC Transactions.

Faulds, J.E., Coolbaugh, M., Bouchot, V., Moek, I., and Oguz, K., 2010, Characterizing structural controls of geothermal reservoirs in the Great Basin, USA, and Western Turkey: Developing successful exploration strategies in extended: Proceedings World Geothermal Congress, , no. April, p. 25–29.

Garg, S.K., Pritchett, J.W., Wannamaker, P.E., and Combs, J., 2007, Characterization of geothermal reservoirs with electrical surveys: Beowawe geothermal field: Geothermics, v. 36, no. 6, p. 487–517, doi: 10.1016/j.geothermics.2007.07.005.

Harinarayana, T., Abdul Azeez, K.K., Murthy, D.N., Veeraswamy, K., Eknath Rao, S.P., Manoj, C., and Naganjaneyulu, K., 2006, Exploration of geothermal structure in Puga geothermal field, Ladakh Himalayas, India by magnetotelluric studies: Journal of Applied Geophysics, v. 58, no. 4 SPEC. ISS., p. 280–295, doi: 10.1016/j.jappgeo.2005.05.005.

Hurst, A.W., and Dibble, R.R., 1981, Bathymetry, heat output and convection in Ruapehu Crater Lake, New Zealand: Journal of Volcanology and Geothermal Research, v. 9, no. 2–3, p. 215–236, doi: 10.1016/0377-0273(81)90005-6.

Lynne, B.Y., 2013, Siliceous sinter: an early exploration tool and direct link to a geothermal reservoir: Thirty-Eight Workshop on Geothermal Reservoir Engineering, p. 1–6.

Neumann van Padang, M., 1951, Catalouge of the active volcanoes of the world including solfatara fields-PartI Indonesia: International Volcanological Association, Napoli, Italy.

de Ronde, C.E.J., Fornari, D.J., Ferrini, V.L., Walker, S.L., Davy, B.W., LeBlanc, C., Caratori Tontini, F., Kukulya, A.L., and Littlefield, R.H., 2015, The Pink and White Terraces of Lake Rotomahana: what was their fate after the 1886 Tarawera Rift eruption? Journal of Volcanology and Geothermal Research, v. 314, p. 126–141, doi: 10.1016/j.jvolgeores.2016.02.003.

Takano, B., Suzuki, K., Sugimori, K., Ohba, T., Fazlullin, S.M., Bernard, A., Sumarti, S., Sukhyar, R., and Hirabayashi, M., 2004, Bathymetric and geochemical investigation of Kawah Ijen Crater Lake, East Java, Indonesia: Journal of Volcanology and Geothermal Research, v. 135, no. 4, p. 299–329, doi: 10.1016/j.jvolgeores.2004.03.008.

Voltattorni, N., Sciarra, A., and Quattrocchi, F., 2010, The Application of Soil-Gas Technique to Geothermal Exploration: Study of Hidden Potential Geothermal Systems: Proceedings World Geothermal Congress 2010 Bali, Indonesia, 25-29 April 2010, , no. April, p. 6 p.

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