Geothermal evidence for groundwater flow through Quaternary sediments overlying bedrock aquifers below Lake Vättern, Sweden

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**ABSTRACT**

Groundwater discharge into lakes is an important component of the fluid and nutrient budgets, and a possible route for contaminant transport. However, groundwater flow beneath lakes is difficult to investigate due to the need for drilling deep boreholes. In 2012, a 2,000 m deep borehole was drilled in Lake Vättern, the second largest lake in Sweden. A continuous temperature profile was collected from the borehole. The geothermal gradient in the upper 180 m is highly non-linear, and not controlled by variability in the measured thermal properties of the sediments and rocks. The anomalous temperature profile is best explained by fluid flow into the borehole and subsequent vertical flow of warm waters towards the lake floor. Combining the temperature profile with stratigraphic information from drilling logs and seismic data, we find that fluid flow into the borehole occurs in glacial and glaciofluvial sediments deposited on top of a large sandstone aquifer (the Visingsö Group). The warm waters flowing through the glacial and glaciofluvial sediments are likely sourced from the underlying Visingsö Group sandstones. There is no evidence for substantial vertical migration of these waters through the overlying glacial and postglacial sediments. We speculate that they escape either along lake margins where overlying sediments become thinner, or along faults that are known to exist in the deeper basin. These results highlight an important hydraulic transport pathway between recognised regional aquifers and Lake Vättern. Further work is needed to evaluate the significance of groundwater discharge on the water and nutrient budget of the lake.

**Introduction**

Lake Vättern is the second largest lake in Sweden and the sixth largest in Europe in terms of area (1,856 km\(^2\)) and volume (74 km\(^3\); Kvärnas 2001) (Fig. 1). It is located in south-central Sweden and stretches over 140 km in an NNE-SSW direction (Fig. 1A). The catchment area is 6,359 km\(^2\), of which the lake comprises approximately 30\% (Fig. 1B). The only outlet from the Lake is Motala Ström (Fig. 1B) where drainage occurs towards the Baltic Sea. Numerous rivers drain into the Lake, with larger rivers near Jönköping (Huskvarnån and Tabergsån) in the south, and in the Northwest by Karlsborg (Forsviksån) (Fig. 1B). Kvärnas (2001) summarized the water balance for the lake, with 612 mm/yr (or 1.14 km\(^3\)/yr) of freshwater input, of which 510 mm/yr (0.95 km\(^3\)/yr) is in the form of precipitation. Annual output amounts to 680 mm/yr (1.26 km\(^3\)/yr), with 442 mm/yr (0.82 km\(^3\)/yr) of evaporation. There is no reason given for the apparent imbalance in yearly inflow and outflow, which may simply reflect uncertainties in the underlying measurements.

The lake is an important source of drinking water, directly supplying about 250,000 people across 11 municipalities. Understanding the source, magnitude and transport pathways of waters into Lake Vättern is required to manage this freshwater resource. Although considerable knowledge exists concerning the geology of the region, little is known about subsurface transport of groundwater below the lake itself. Submarine and lacustrine groundwater discharge are increasingly being recognised as an important component of the hydrogeological cycle (Destouni et al. 2008; Bratton 2010; Kornelsen & Coulibaly 2014). While sometimes volumetrically small, these discharges can have a considerable impact on nutrient budgets for inland and enclosed waterbodies (Kornelsen & Coulibaly 2014; Rodellas et al. 2015; Rudnick et al. 2015).

Lake Vättern lies on the stable Baltic Shield, which is part of the East European Craton. The Baltic Shield is characterised by relatively low surface heat flow (35–45 mW/m\(^2\)) compared to surrounding areas in Europe (Cermák et al. 1993). Although few measurements exist from central and southern Sweden, gridded and contoured data suggest a general increase in surface heat flow across the Baltic Shield towards the southwest, approaching 60–70 mW/m\(^2\) in the region of Lake Vättern (Cermák et al. 1993; Artemieva & Mooney 2001; Näslund et al. 2005). The Vättern basin is located along the Transscandinavian Igneous Belt (Högdahl et al. 2004), within a zone of extinct shear deformation that separates two major lithotectonic provinces, the Fennoscandian foreland, which is part of the Svecofennian orogeny, and the eastern segment of the younger Sveconorwegian orogeny, which both occurred in the Palaeoproterozoic (Johansson & Johansson 1990; Brander et al. 2012; Andréasson & Rodhe 1990; Wik et al. 2006; Bingen et al. 2008). Lake Vättern occupies a graben (De Geer 1910; Axberg & Wadstein 1980; Lind
of Sweden (SGU) recognises the Visingsö Group as a potentially prolific groundwater reservoir with an exploitation potential of 2000–6000 l/hr (http://apps.sgu.se/kartvisare/kartvisare-grundvatten-1-miljon-en.html, accessed 06/15/2016) (Fig. 2C).

Quaternary sediments surrounding the lake are composed of various glacial and glaciolacustrine sediments deposited by the Fennoscandian ice sheet (Lundqvist & Wohlfarth 2001; Wohlfarth et al. 2008). In many places these overlie the Visingsö Group sandstones (Fig. 2B). Both the surficial Quaternary sediments and the Visingsö Group sandstones are recognised as regional aquifers (Fig. 2C). The combination of highly permeable Quaternary deposits on top of the sandstones creates, in some regions, a continuous aquifer (Persson 2014). On the western and southwestern shores of the lake, granitic bedrock is either exposed or covered by thinner glacial and glaciofluvial deposits (Fig. 2). The granite bedrock is believed to hold substantially less groundwater than the Visingsö Group sandstones. The Visingsö Group extends beneath Lake Vättern; however, there is no information on how confined this aquifer is and to what extent it may be discharging groundwater into the lake.

Heat can be used as a tracer of fluid flow (e.g., Anderson 2005; Rau et al. 2013). Where subsurface variations in temperature exist along a flow path, the flowing water will transport heat between them. Since water has a high heat capacity, even fairly minor rates of fluid flow can result in considerable thermal perturbations (Bredhoef & Papadopulos, 1965; Drury et al. 1984; Anderson 2005). During the period July–September 2012, a 2,000 m deep borehole was drilled in southern Lake Vättern from a barge anchored offshore of Jönköping (Fig. 1). A temperature profile was obtained from this borehole at the end of drilling. Here we combine this temperature log with thermal property measurements on recovered sediments and rocks to evaluate the origin of subsurface temperature anomalies and their possible association with groundwater flow beneath Lake Vättern.

Methods

Borehole drilling

Between June 29 and 26 September 2012, Asera Mining AB drilled a 2,000 m deep borehole in the southern part of Lake Vättern (Bh32012) at a water depth of ~90–95 m (Fig. 1). Prior to drilling, casing with an outer diameter (OD) of 139.7 mm and an inner diameter (ID) of 127.0 mm, was set from the barge deck (1.65 m above the water line) to a depth of 108 m below the barge deck (~57 m below the lake floor, mblf). The second set of casing (OD 114.3 mm, ID 101.6 mm) was inset to a depth of 207 m below the barge deck (~110 mblf). Drilling was done within this dual casing system using drilling rods having an OD of 88.9 mm and an ID of 77.8 mm. Sediments and rocks were sampled using a 3 m wireline drilling system, with sediments collected in plastic liners (OD 65 mm and ID 63 mm). The borehole penetrated 440 m of lake sediments and sedimentary rocks and extended a further 1,560 m into igneous bedrock, mainly diorite. Following the completion of the borehole, the drilling rods and inner casing were removed from the borehole. The large

1972) that formed 700–800 million years ago (Ma) during a period of extensional faulting (Andréasson & Rodhe 1990).

The bedrock around Lake Vättern is dominated by igneous rocks, primarily granites and granitoids (Fig. 2A). However, within the lake basin these are overlain by up to 1,000 m of the 700–850 Ma Visingsö Group, a remnant of a > 8,000-m thick sedimentary platform that covered southeastern Sweden during the Neoproterozoic era (Norman 1964; Axberg & Wadstein 1980; Vidal 1984; Andréasson & Rodhe 1990) (Fig. 2A). The Visingsö Group consists of three vertically stacked subunits with sandstone and shale as the dominating rock type but also including minor occurrences of clastic conglomerates and limestones (Collini 1951; Vidal 1976, 1984). The boundary between the crystalline bedrock and the Visingsö Group has been described as a denudation surface (Collini 1951) with the successive subunits deposited under fluvial-deltaic to marine conditions (Collini 1951; Vidal 1976, 1984). The Geological Survey

Figure 1. A. Location of Lake Vättern in Sweden. B. Topographic and bathymetric setting of Lake Vättern with the location of the Levene moraine and MSEMZ (Middle Swedish End Moraine Zone) formed during the deglaciation of the Fennoscandian Ice Sheet in the Lake Vättern region. Bh32012 indicates the drilling site, with the dashed line indicating the approximate position of the seismic line shown in Figure 4.
Figure 2. Geology and hydrogeology of southern Lake Vättern region. A. Bedrock distribution. B. Surficial sediment distribution. C. Groundwater reservoirs in bedrock and surficial sediments based on data from the Geological Survey of Sweden (SGU). Arrows indicate the primary direction of groundwater flow. Dashed-red lines are hydrogeological divides. Maps downloaded and modified from http://apps.sgu.se/kartvisare/kartvisare-grundvatten-1-miljo-en.html.
**Fluid temperature logging**

On October 23, 4 weeks after drilling was completed, a temperature profile was obtained under natural conditions by lowering an ANTARES miniature temperature logger (Pfender & Villinger 2002) on the wellline. The ANTARES probe has a thermal operational range between −5 °C and 60 °C and can withstand pressures up to 60 MPa. It was lowered at a mean rate of 0.47 m/s (±0.15 m/s 1σ) to a depth of 1950 m below the rig floor (mbrf). Lowering speeds were calculated by manually recording the time for each 10-m lowering of the winch. Temperature measurements were logged every second during the lowering and raising of the temperature probe, providing between 2 and 3 temperature measurements per meter. Because casing only remained in the upper 57 m of the borehole, the profile is an open-hole temperature log.

**Coring of unconsolidated sediments**

After the temperature profiling, five additional closely spaced boreholes were drilled in the unconsolidated Quaternary sedimentary cover, the deepest reaching 74 m below lake floor, at a water depth of 98 m (position 14° 11.05'E, 57° 50.00'N). These boreholes were drilled in an attempt to obtain a near complete late Pleistocene – Holocene sedimentary sequence. Detailed sedimentological, geochemical and geotectonic analyses of these sediments were used to reconstruct deglacial and Holocene environmental changes in Lake Vättern (Swärd et al. 2016, 2018), and to further constrain ice dynamics in the Vättern region during deglaciation (Greenwood et al. 2015; O’Regan et al. 2016).

**Thermal properties of sediments and rocks**

The thermal properties (thermal conductivity, specific heat capacity, and thermal diffusivity) of the recovered unconsolidated sediments and sedimentary and igneous rocks were measured using the transient plane source technique (Gustafsson et al. 1979) at Stockholm University and Chalmers University, respectively. At both institutes, a HotDisk TPS system, manufactured by K-analysis in Uppsala, Sweden, was used. All measurements were performed on water-saturated samples. The thermal properties of the sandstone and igneous bedrock were measured on 18 rock samples from different borehole depths. An additional 69 measurements were performed at Stockholm University on sediments from the upper 70 mblf. Results from the thermal property measurements were published by Sundberg et al. (2017). A summary and description of how they were implemented in this manuscript are provided in the Results section below.

**Heat flow calculations**

In a conduction-dominated system, heat flow is approximated by the product of the vertical temperature gradient and the thermal conductivity of the material (Fourier’s Law),

\[ Q = \lambda \frac{dT}{dz} \] (1)

where \( Q \) is the surface heat flow (W/m²), \( \lambda \) is the thermal conductivity (W/mK) and \( \frac{dT}{dz} \) is the temperature gradient (°C/m). Heat flow can also be obtained as the slope of the best-fitting line to a “Bullard plot” (Bullard 1939) of temperature versus thermal resistance (Ω, m²K/W),

\[ Q = \frac{dT}{d\Omega} \] (2)

where

\[ \Omega = \int_0^z \frac{dz}{\lambda(z)} \] (3)

In the thermal modelling presented in this paper, both approaches are used. Fourier’s Law is used to define the background heat flow through the igneous bedrock, where the temperature gradient is linear. The Bullard method is used to investigate whether changes to the temperature gradient can be explained by variations in the thermal properties of the sediments and rocks.

**Results**

**Lithology and stratigraphy**

Igneous rocks were encountered between the base of the borehole and 341 mblf. These were mostly dolerites with high mafic mineral composition. An exception to this is the interval between 1395 and 1360 mblf, were the igneous rocks had higher silica content (granodiorite) (Table 1) (Fig. 3). Sandstones belonging to the Visingsö Group were recovered between 341 and 155 mblf (Fig. 3). No sediment was retained from the upper 155 m of the borehole, but the drilling logs indicate that at 86.5 mblf, sandy-sediments were encountered, and that between 111 and 155 mblf, pebble and cobble-sized clasts of sandstone and ultramafic/mafic rocks exist.

The near continuous composite stratigraphy from the five shallow boreholes extends to 74 mblf (Swärd et al. 2016). Three primary sedimentary units were described in the composite sequence from these boreholes (Swärd et al. 2016, 2018). These include 1) An organic-rich, silty-clay interpreted as a lacustrine clay; 2) sulphide laminated, silty clay deposited in a post-glacial environment and; 3) laminated silty-clays with low organic carbon content, deposited in a glacial/pro-glacial lake environment (Swärd et al. 2016). A sharp unconformity above visibly deformed, highly overconsolidated sediments exist at 55 mblf. This is interpreted as the last time that glacial ice was in contact with the lake floor (O’Regan et al. 2016; Swärd et al. 2016; Greenwood et al.

| Depth below lake floor (m) | Unit(s) | Predominant lithology |
|---------------------------|---------|-----------------------|
| 0–15                      | 1       | Lacustrine clays (Quaternary) |
| 15–25                     | 2       | Post-glacial silty-clay (Quaternary) |
| 25–55                     | 3       | Pro-glacial silty-clay (Quaternary) |
| 55–155                    | 4       | Glacial and glacifluvial (Quaternary) |
| 155–341 m                 | 5       | Sandstone |
| 341–1820 m                | 6       | Diorite |
| 1266–1296 m               | 7       | Granodiorite |
The silty-clays above this glacial unconformity (55–25 mblf) contain cyclic changes in sediment texture and composition, interpreted as varves deposited in a pro-glacial lake setting (Swärd et al. 2016). The sulphide laminated post-glacial clays (25–15 mblf) were deposited in a brackish water environment following the final drainage of the Baltic Ice Lake (Swärd et al. 2016, 2018). This brackish water phase is evidenced by elevated salinities measured in the pore waters of the recovered sediments (Swärd et al. 2016). The upper 15 m of the sequence is composed of low carbonate content, diatom-bearing gyttja clay, deposited after isostatic adjustments isolated Lake Vättern from the Littorina Sea at 9530 ± 50 cal. a BP (Swärd et al. 2018).

Integrating the borehole lithology with seismic data, Greenwood et al. (2015) show that approximately 100 m of glacially deposited and overridden sediments exist in the vicinity of the drilling sites. These sediments, seismic Unit S3 to S5, are capped by the ~55 m of pro-glacial, postglacial and lacustrine clays described in the composite sedimentary profile (Swärd et al. 2016, 2018; O’Regan et al. 2016) (Fig. 4).

Therefore, from the top of the Visingsö Group sandstones at 155 mblf to 55 mblf, the sediments are considered Quaternary in age and are composed of glaciotectonized pro-glacial, glacial and glaciofluvial sediments. Based on a detailed regional seismic interpretation, these sediments were likely overridden by at least two ice advances, and in some parts of southern Lake Vättern (including the drilling site) attain thicknesses >180 m (Greenwood et al. 2015) (Fig. 4). The lowermost seismic unit (S5) only occupies the deep trough of Lake Vättern. It has a variable thickness and undulating upper contact with S4 (Fig. 4). It is defined by having a chaotic internal reflection character lacking any acoustic stratification but containing intervals of high amplitude planar reflectors (Greenwood et al. 2015). These sediments are interpreted to be subglacial diamicts with possible glaciofluvial and ice-proximal components (Greenwood et al. 2015). This interpretation is consistent with the drilling logs that reported the presence of cobble-sized clasts of sandstones and ultra-mafic rocks between 155 and 111 mblf. Throughout this manuscript, sediments from below the recovered ice-contact horizon at 55 mblf, are cumulatively
described as glacial and glaciofluvial sediments, although we recognise a significant amount of possible depositional and sedimentological variability within this broad classification.

**Temperature profile**

The temperature profile for the water column, obtained through the casing, closely approximates the average October profile from the Edskvarnation NV site (located at 57° 54.45’ N, 14° 13.75’ E), roughly 9 km away from the drilling site (Fig. 1B). This provides an initial quality control check on the thermal profile for the remaining borehole (Fig. 5). The lake floor is recognised by an abrupt drop in temperature at approximately 96 m below the lake surface.

Below the lake floor, the geothermal gradient varies through the Quaternary sediments and underlying sandstones, and stabilizes into a very linear gradient in the igneous bedrock (Fig. 3). From 500 mblf to the base of the borehole, a gradient of 18.3 °C/km ($r^2 = 0.9990$) is found (Fig. 3). In the Visingsö Group sandstones, the temperature gradient lowers considerably to 7.7 °C/km ($r^2 = 0.9991$) between 300 and 200 mblf (Fig. 3). Between ~180 and 110 mblf the temperature profile is highly non-linear and interrupted by two pronounced small amplitude warm temperature anomalies (0.3–0.5 °C). These occur within the lower part of the glacial and glaciofluvial sediments, correlating to seismic unit S5 (Figs. 3, 4). From ~110 to 55 mblf, a linear gradient of 15.9 °C/km ($r^2 = 0.9964$) exists. Numerous sharp changes in the geothermal gradient occur above 55 mblf. Temperatures below the seafloor (6.4 °C) quickly cool to a minimum of (5.7 °C) at 2.8 mblf where temperatures begin to increase non-linearly towards 10 mblf (6 °C). These shallow perturbations likely originate from seasonal variations in bottom water temperatures (see discussion) (Fig. 3).

The sharp inflections in the temperature profile between 55 and 20 mblf coincide with substantial changes in the lowering speed of the probe (Fig. 3). The lowering speed was highest (>1.2 m/s) between 20 and 40 mblf, and likely did not allow the probe to equilibrate with the ambient temperature. At 40 mblf, the lowering speed was slowed considerably (<0.35 m/s). The rapid increase in measured temperature between 40 and 55 mblf is therefore interpreted as an artefact of the sensor re-equilibrating to the ambient temperature (Fig. 3). A linear interpolation between temperatures at 55 and 20 mblf is used to acquire an estimate of the geothermal profile across this interval (Fig. 3). Below the depth at which the temperature probe re-equilibrated to *in situ* conditions (~55 mblf) the remaining borehole temperature data is considered reliable as there are no intervals where the lowering speed exceeds 0.6 m/s (Fig. 3).

**Thermal conductivity measurements**

The average thermal conductivity of the igneous bedrock was determined from 16 measurements performed on the diorite and granodiorite samples to be 2.25 ± 0.28 W/mK (Table 2, Fig. 3). This falls within the range reported for diorites (1.4–4.2 W/mK) (Roy et al. 1981; Eppelbaum et al. 2014) (Table 2). The two measurements on sandstone samples (3.36 and 2.39 W/mK) provide a mean thermal conductivity of 2.88 W/mK, again within the range of reported values (2.0–4.5 W/mK) (Blackwell & Steele 1989; Anderson 2005; Rühaa et al. 2015). Through the upper sedimentary section, thermal conductivity generally increases downhole, with an average value of 1.25 W/mK (Table 2, Fig. 6).

| Drill site lithology | Two way travel time (ms) |
|----------------------|--------------------------|
| S1                   | 500                      |
| S2                   | 600                      |
| S3                   | 700                      |
| S4                   | 800                      |
| S5                   | 900                      |
| S6                   | 1000                     |
| S7                   | 1100                     |
| S8                   | 1200                     |
| S9                   | 1300                     |
| S10                  | 1400                     |
| S11                  | 1500                     |
| S12                  | 1600                     |
| S13                  | 1700                     |
| S14                  | 1800                     |
| S15                  | 1900                     |
| S16                  | 2000                     |
| S17                  | 2100                     |
| S18                  | 2200                     |
| S19                  | 2300                     |
| S20                  | 2400                     |
| S21                  | 2500                     |
| S22                  | 2600                     |
| S23                  | 2700                     |
| S24                  | 2800                     |
| S25                  | 2900                     |
| S26                  | 3000                     |
| S27                  | 3100                     |
| S28                  | 3200                     |
| S29                  | 3300                     |
| S30                  | 3400                     |
| S31                  | 3500                     |
| S32                  | 3600                     |
| S33                  | 3700                     |
| S34                  | 3800                     |
| S35                  | 3900                     |
| S36                  | 4000                     |
| S37                  | 4100                     |
| S38                  | 4200                     |
| S39                  | 4300                     |
| S40                  | 4400                     |
| S41                  | 4500                     |
| S42                  | 4600                     |
| S43                  | 4700                     |
| S44                  | 4800                     |
| S45                  | 4900                     |
| S46                  | 5000                     |
| S47                  | 5100                     |
| S48                  | 5200                     |
| S49                  | 5300                     |
| S50                  | 5400                     |
| S51                  | 5500                     |
| S52                  | 5600                     |
| S53                  | 5700                     |
| S54                  | 5800                     |
| S55                  | 5900                     |
| S56                  | 6000                     |
| S57                  | 6100                     |
| S58                  | 6200                     |
| S59                  | 6300                     |
| S60                  | 6400                     |
| S61                  | 6500                     |
| S62                  | 6600                     |
| S63                  | 6700                     |
| S64                  | 6800                     |
| S65                  | 6900                     |
| S66                  | 7000                     |
| S67                  | 7100                     |
| S68                  | 7200                     |
| S69                  | 7300                     |
| S70                  | 7400                     |
| S71                  | 7500                     |
| S72                  | 7600                     |
| S73                  | 7700                     |
| S74                  | 7800                     |
| S75                  | 7900                     |
| S76                  | 8000                     |
| S77                  | 8100                     |
| S78                  | 8200                     |
| S79                  | 8300                     |
| S80                  | 8400                     |
| S81                  | 8500                     |
| S82                  | 8600                     |
| S83                  | 8700                     |
| S84                  | 8800                     |
| S85                  | 8900                     |
| S86                  | 9000                     |
| S87                  | 9100                     |
| S88                  | 9200                     |
| S89                  | 9300                     |
| S90                  | 9400                     |
| S91                  | 9500                     |
| S92                  | 9600                     |
| S93                  | 9700                     |
| S94                  | 9800                     |
| S95                  | 9900                     |
| S96                  | 10000                    |

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**Table 2.** Thermal properties of sediments and rocks measured using the Transient plane source (TPS) method. Complete data sets are published in (Sundberg et al. 2017).

| Lithology                | Th. conductivity (W/mK) | Th. diffusivity (mm²/s) | Specific heat (MJ/m³/K) |
|--------------------------|-------------------------|-------------------------|-------------------------|
| Quaternary               | 1.25 ± 0.19             | 0.41 ± 0.13             | 3.10 ± 0.31             |
| Visingsö Group sandstones| 2.88                    | 1.24                    | 2.33                    |
| Diorites                 | 2.25 ± 0.28             | 1.03 ± 0.09             | 2.19 ± 0.14             |

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Figure 4. Seismic reflection profile across the drill site (line 14, from Greenwood et al. 2015). The lithologic column from drilling overlain, alongside the interpreted seismic units of Greenwood et al. (2015). The base of the sandstone unit cannot be seismically identified and is calculated from the TWT using a compressional wave velocity of 2500 m/s. Note how the Quaternary sediments (lithologic units 1–4) thin significantly near the lake margins.
Due to the large changes in the geothermal gradient, a heat flow estimate for the sedimentary section is not presented. However, applying the Bullard Method, it is apparent that there are no sharp changes in the thermal resistance profile that could explain the rapid inflections in the geothermal gradient between 55 and 20 mblf (Fig. 6). This further supports the interpretation that these thermal changes are artefacts arising from the rapid lowering speed through this interval of the borehole.

Discussion

Influence of seasonal bottom water temperature variations

Seasonal changes in bottom water temperatures (BWT) can have a profound effect on temperatures in the upper meters to decimetres of marine and lacustrine sediments. To model this effect at the Vättern borehole, a sinusoidal function was fit to observational data using measurements from the Edeskvarnaån NV site between 1972 and 2003 (Fig. 7). This monitoring site provides seasonal water column measurements down to 115–120 m but does not include measurements from December through March.

To overcome this data gap, the average daily temperatures ($T$, °C) are fit by a sine function

$$T = 1.919 \sin \left( \frac{2 \pi}{365} \text{day} + 15.662 \right) + 0.948 \sin \left( \frac{2 \pi}{365} \text{day} + 15.315 \right) + 4.136$$

The function captures the two annual phases of bottom water warming in Vättern (Fig. 7). These occur in the spring, prior to the development of a weak and shallow thermocline, and in the fall, when overturning occurs due to storm-induced surface water mixing and cooling (Kvärnas 2001). Using only the available measurements, the yearly average BWT is 4.7 °C, decreasing to 4.14 °C if the modelled profile is used (Fig. 7).

Using an average BWT of 4.14 °C, a background heat flow of 41 mW/m², and the thermal resistance profile for the upper 70 mblf, the predicted in situ temperature profile under purely conductive conditions is modelled using Equation (3) (Fig. 8). Seasonal changes in BWT are largely confined to the upper 4–8 m (Fig. 8), and cannot account for the warm borehole temperatures between 70 and 10 mblf. The modelled temperature profile captures the seasonal variations in shallow sediments, and the overall shape fits nicely with the observed profile. There is, however, a large offset between the two, with the predicted temperature being far cooler than the measured profile.

Reconciling the modelled and observed temperature gradients would require the average bottom water temperature to be increased by 1.2–1.6 °C. This is considerably higher than the average temperature (4.7 °C) calculated from the observational data that does not include measurements between December and March (Fig. 7). Therefore, we do not think that errors in the BWT calculation can explain all of the observed offset.

Uncertainty in the average BWT does exist because the data set only extends to 2003. Because of this, we cannot constrain the impact of possible warming between 2003 and 2012. Furthermore,

**Heat flow calculations**

Heat flow calculated using Fourier's Law over discrete 100 m intervals in the diorite section of the borehole increases from 35 to 45 mW/m² (Sundberg et al. 2017). In the thermal modelling undertaken here, we use the linear temperature gradient (18.3 °C/km) through this same dioritic section (Fig. 4) and the average $\lambda$ of the diorites (2.25 ± 0.28 W/mK) to obtain a heat flow of 41 ± 5 mW/m² (equation (1)). This is necessary to derive a uniform value for the heat flow that can be used in modelling and which comes close to encompassing the reported range of values by Sundberg et al. (2017). The heat flow value determined from the Vättern borehole (35–45 mW/m²) is lower than anticipated from regional compilations of the Baltic Shield which predict a heat flow between 60 and 70 mW/m2 for this region of Sweden (Cermák et al. 1993; Artemieva & Mooney 2001; Näslund et al. 2005). However, no detailed investigation into the underlying cause for this mismatch has been conducted.
we have not removed any long-term warming trend from the observational time series. Satellite-based estimates of yearly average surface water temperature warming in Lake Vättern indicate a 0.46 °C/decade trend between 1981 and 2016 (Lieberherr & Wunderle 2018). However, surface warming of ~1.5 °C between 1981 and 2011 does not translate to an equivalent bottom water warming, which will affect the subsurface temperature profile. Never-the-less, these longer-term warming trends may contribute to the offset between the modelled and observed geothermal gradients. On the other hand, it is worth noting that our temperature profile through the water column very closely approximated the average measured October water column temperatures from 1972–2003 (Fig. 5). This further suggests that BWT warming may only account for a limited amount of the offset between the measured and modelled borehole temperatures.

For comparative purposes, the modelled temperature profile is extended to 500 mblf by assuming reasonable thermal conductivities for the poorly recovered glacial/glaciofluvial sediments and underlying sandstones. Three models are used where the thermal conductivity of the glacial/glaciofluvial sediments varies between 2 and 3 W/mK and the sandstones from 2 to 4.5 W/mK (Table 3). Model III provides the best fit to the observed temperature profile, but an absolute temperature offset persists until 500 mblf (Fig. 8B).

Figure 6. Downhole data for the upper 70 m of the sedimentary column, where near-continuous recovery was achieved. A. Temperature, thermal conductivity and thermal resistance profile for the upper 70 mblf. B. Bullard plot, illustrating that the non-linear nature of the geothermal gradient in the upper 70 mblf is not a function of changing sediment thermal properties, as this would produce a linear relationship between thermal resistance and in situ temperature.

Figure 7. Comparison of modelled seasonal BWT and observations from Edeskvarnaån NV. Raw data is shown by the yellow circles. Average monthly temperatures and standard deviations are given by the black squares. Grey boxes bracket probable range and uncertainty of monthly temperatures, especially large during the late fall and winter when few measurements exist.
Evidence for lateral flow into the borehole from glacial sediments

The temperature profile displays a clear transition from one dominated by quasi-steady state conduction to a highly perturbed and non-linear gradient in the upper 180 mblf (Fig. 3). The most notable perturbations to the temperature profile occur between 180 and 110 mblf. Two broad zones of positive temperature anomalies are present that suggest lateral fluid flow into the borehole, as is commonly reported in regions where subsurface fluids flow in fractured media (Ge 1998; Bense et al. 2008; Börner & Berthold 2009; Klepikova et al. 2011; Bense et al. 2013). These temperature anomalies are positive, indicating inflow of warmer fluids (Fig. 3). The regions of inflow are located within the glacial and glaciofluvial sediments overlying the Visingö Group sandstones. This inflow is considered the likely source for the anomalously warm borehole conditions found above, and the low geothermal gradient found within the underlying Visingö Group sandstones.

The low-temperature gradient within the underlying sandstones may also be an artefact from this fluid invasion. For example, with a background heat flow of 41 mW/m², sustaining the observed temperature gradient through the sandstone unit (7.70 °C/km) requires an average thermal conductivity of 5.27 W/mK (Equation (1)). This is considerably higher than the two measured values from the sandstones (3.36 and 2.39 W/mK), and generally high compared to the reported range of conductivities for sandstones.

Due to the warm temperatures, the fluids entering the borehole between 180 and 110 mblf are likely sourced from deeper lying strata. Direct lateral transport from onshore regions is not considered likely as Quaternary sediments thin and become discontinuous towards the margins of the lake. Therefore, they do not provide a laterally continuous and/or confined conduit for fluid flow from land. This is evident in our geophysical profiles across...
Vertical fluid velocities within the borehole and anomalous warmth

Here we investigate whether the vertical flow of warm fluids entering the borehole between 180 and 110 mblf can realistically account for the difference between the measured and modelled temperature profiles. To address this, the rate of inflow to the borehole is approximated using additional modelling. Ramey (1962) provided an analytic solution for deriving the thermal influence of fluid injection and vertical migration within a borehole (Fig. 9). Above an injection point, the temperature at any point (T) can be approximated by

\[ T = T_e + 2 \frac{dT}{dz} \exp \left( -\frac{z}{A} - 1 \right) A \frac{dT}{dz} \]  

(4)

where \( T_e \) is the temperature of fluids entering the borehole, \( z \) is the vertical distance from the fluid entry point and \( \frac{dT}{dz} \) is the normal temperature gradient. A time dependent parameter (A) represents the rate of heat transfer between the moving fluid and surrounding formation (Ramey 1962; Drury et al. 1984).

\[ A = V c_p f(t) \frac{f(t)}{2\pi\lambda} \]  

(5)

where \( V \) is a measure of the rate of flow into the borehole (kg/s), \( c_p \) is the specific heat capacity of the fluid (4180 J/kgK), \( \lambda \) the thermal conductivity for the formation and \( f(t) \) a dimensionless time function:

\[ f(t) = -\ln \left( \frac{r}{\sqrt{2\pi \alpha t}} \right) - 0.29 \]  

(6)

where \( t \) is the time since the end of drilling (26 days or 2,246,400 s), \( r \) the radius of the borehole (0.044 m) and \( \alpha \) the thermal diffusivity of the formation.

The relationship between measured thermal conductivity and thermal diffusivity in the upper 74 m of the borehole is used to derive estimated average values for the modelling (Fig. 10). Two scenarios are modelled, where the thermal conductivity is assumed to be 1.8 W/mK (\( \alpha = 0.639 \text{ mm}^2/\text{s} \)) and 1.4 W/mK (\( \alpha = 0.468 \text{ mm}^2/\text{s} \)).

Type curves are derived for the predicted temperature profiles resulting from different injection rates at point source locations of either 180 mblf (\( T_e = 8.1 \text{ °C} \)) or 110 mblf (\( T_e = 7.8 \text{ °C} \)) (Fig. 10). Background temperature gradients for the two cases (110 m = 33 °C/km and 180 m = 22 °C/km) are defined using a linear fit between the temperature at the depth of water injection, and the mean lake floor temperature of 4.14 °C. The resulting modelled thermal profiles are compared to the observed temperatures. Injection rates of 0.01–0.05 kg/s (or 10–50 cm³/s assuming a fluid density of 1000 kg/m³) best explain the warm borehole temperatures above 180–110 mblf (Fig. 11). Dividing these by the area of the borehole (0.006207 m²) results in vertical flow velocities (\( v_{bh} \)) of 2–8 mm/s. These flow rates would be lower if the average bottom water temperature used in the calculation (4.14 °C) is actually higher due to poor representation of winter temperatures, or if warming has occurred in the past decade(s).

Estimated lateral fluid velocity and required hydraulic gradients

Further modelling is used to investigate the potential lateral velocity of groundwater through the glacial and glaciofluvial sediments, and the hydraulic head required to drive this flow. An estimate of the lateral fluid velocity invading the borehole can be obtained by dividing the specific discharge into the borehole by the porosity of the formation.

The specific discharge (q) of fluid into the borehole depends on the surface area (borehole circumference (0.279 m) x length) through which the fluid flows. A minimum length over which

![Figure 9. Schematic illustration of how vertical fluid velocity was calculated using the model of Ramey (1962). A linear geothermal gradient, constrained by a fixed temperature at the top and base is disturbed by vertical fluid flow in a borehole. The resulting gradient depends on the vertical velocity of the water in the borehole (V), the temperature at the injection point (T_e), and the rate at which the borehole water is equilibrating with the surrounding formation. This can be estimated knowing the specific heat capacity of water (c_p), the average thermal conductivity (\lambda) and diffusivity (\alpha) of the formation.](image)

![Figure 10. Correlation between measured thermal conductivity and thermal diffusivity of sediments from the upper 74 m of the Vättern borehole.](image)
Fluids are flowing into the borehole of 20 m, and a maximum of 70 m (i.e., 110–180 mblf) results in \( q_{\text{min}} = 5.1 \times 10^{-5} \text{ cm/s} \) and \( q_{\text{max}} = 9.0 \times 10^{-4} \text{ cm/s} \). The porosity of sediments between 180 and 110 mblf is not available, so a reasonable range of 20–40% is assumed, based on reported values for sands and gravels. Dividing the specific discharge by this range of porosities results in estimated lateral velocities that range from 1.3 × 10^{-4} to 4.5 × 10^{-3} cm/s or between 40 and 1411 m/yr.

The required hydraulic gradient needed to drive flow rates of this magnitude can be roughly estimated using the specific discharge \( q \) into the borehole and Darcy’s Law

\[
q = -K \frac{dh}{dl}
\]

where \( K \) is the hydraulic conductivity (m/s) and \( dh/dl \) the hydraulic gradient. In these calculations, the \( dl \) is the flow path length from the point of recharge to the borehole. We assume that this length scale may vary from anywhere between 1 and 10 km. Solutions for the total head \( dh, m \) required to achieve the calculated flow rates are therefore provided for lengths \( dl \) of 1,000, 5,000 and 10,000 m, and a range of \( K \) (1×10^{-6} to 5×10^{-2} m/s) representative of clean sand and gravel deposits (Freeze & Cherry 1979) (Fig. 12). Over these distances, the estimated specific discharge (5.1×10^{-5} cm/s to 9.0×10^{-4} cm/s) can be maintained through highly permeable clean sand and gravel deposits under relatively small total heads of 10–50 m.

Once again, the estimated flow rates and required total heads are lower if we have underestimated the average BWT. In spite of this uncertainty, the two modelling exercises show that the vertical fluid velocities required to account for the anomalously warm borehole temperatures can be maintained by lateral flow over distances of 1–10 km and driven by moderate head differences.

**Groundwater flow beneath Lake Vättern**

Our interpretation of groundwater flow is based on two observations, 1) the anomalously warm borehole temperatures found in the upper 70 m of the borehole and more importantly, 2) the observation that this excess heat can be tied to a series of relatively rapid temperature fluctuations that occur through the lower portion of the glacial and glaciofluvial sediments. Terrestrial studies surrounding Lake Vättern suggest that groundwater
infiltration occurs through Quaternary sediments that directly overly the Visingsö Group sandstones (Fig. 2C) (Persson 2014). Our interpretation from the borehole temperature profile is that glacial and glaciofluvial sediments below much of Lake Vättern remain hydraulically connected to the underlying sandstone aquifer (Fig. 13). The fact that thermal indications on fluid infiltration into the borehole are only seen within the Quaternary sediments and not within the Visingö Group sandstones indicates that they have a higher overall permeability and provide an important conduit for groundwater flow beneath the lake.

We suggest that geothermally warmed groundwater enters the confined Quaternary sediments below the lake through the Visingö Group sandstones. How this occurs remains speculative. The absence of notable fluid flow into the borehole from the Visingö Group sandstones suggests that at this location of the lake they are not highly transmissive. It is possible that other sections of the Visingö Group are more permeable, and may be in contact with the glacial and glaciofluvial sediments away from the drilling site.

Alternatively, fluid transport may be focused along pre-existing fractures. The faulted nature of the Visingö Group is a consequence of the extensional tectonics that originally formed the basin and is seen in outcropping sections that surround the lake (Axberg & Wadstein 1980; Vidal 1984). While fracture flow has been investigated in lower permeability carbonate and crystalline formations, it is increasingly being recognised as an important component of fluid transport through sandstone aquifers (Gellasch et al. 2013; Medici et al. 2016, 2018). However, the transmissivity of fractures is not straightforward, and they can either be barriers to or preferential pathways for fluid transport (Knipe et al. 1998; Bense et al. 2013; Lo et al. 2014). This can depend on the fault aperture and fault network density, time since formation, degree of dissolution/cementation, and local stress orientations within the formation (Bense et al. 2013). Currently, we lack necessary data on the regional fault geometries and

Figure 12. Total head (dh) required to maintain estimated low (5.1x10^{-5} cm/s) and high (9x10^{-4} cm/s) specific discharge into the borehole through the glacial and glaciofluvial sediments. As the length of the flow path increases, the total head needed to drive flow increases. Results are shown for distances (dl) of 1, 5 and 10 km, through sediments with hydraulic conductivities typical of clean sands and gravels. The shaded area highlights the hydraulic conductivities over which moderate dh values (10-50 m) can sustain the estimate specific discharge rates.

Figure 13. Schematic model of possible groundwater flows below southern Lake Vättern. The diagram is not to scale. Proposed infiltration of groundwater into the Visingö Group sandstones occurs in outcropping sections on land (a). percolates through surficial sediments (b), or may be fed through fracture flow from the underlying igneous bedrock (c). Beneath Lake Vättern this groundwater flows back into the thick glacial and glaciofluvial sediments. We suggest that it escapes to the lake floor where the postglacial overburden thins on the lake margins (d), or faulting has created more highly permeable vertical conduits (e).
characteristics of borehole rocks needed to address these questions.

On the other hand, seismic and coring evidence from lake Vättern suggests that some of the pre-existing extensional faults underlying the lake were reactivated by neotectonic activity following the withdrawal of the Fennoscandian ice sheet (Jakobsson et al. 2014, 2016). Relatively recent re-activation of extensional faults may provide the connected open fracture network needed for fluid transport into the overlying glacial and glaciofluvial sediments (Knipe et al. 1998). The absence of temperature spikes in the borehole through the Visingö Group sandstones implies that the borehole did not intersect zones of fluid transport in active faults. Therefore, fluid transport through fractured zones in the bedrock remains speculative.

Eventually, groundwater flowing through the glacial and glaciofluvial sediments must escape from the lake floor. The pore water chemistry from sediments in the upper 55 mblf does not reveal any evidence for extensive vertical migration of pore waters. In fact, Swärd et al. (2016) show that the pro-glacial and post-glacial sediments retain a saline signature from the time that Lake Vättern was connected to the Yoldia and Littorina Seas, following the drainage of the Baltic Ice Lake.

The relatively thick deposits of pro-glacial and post-glacial silty clays in the deeper parts of the basin likely act as an aquitard. Discharge may then occur where the pro-glacial to lacustrine overburden thins or where recently formed fractures extend towards the seafloor above reactivated faults in the bedrock (Jakobsson et al. 2014, 2016) (Fig. 13). This implies the widespread lateral transport of groundwater into the glacial and glaciofluvial sediments overlying the Visingö Group sandstones, and its migration towards the basin margins, where overburden thins. A similar groundwater transport system is reported around the Great Lakes in North America where groundwater flow occurs in glaciofluvial sediments beneath and between the lakes (Hoaglund et al. 2002). Like in the Vättern area, these glacial deposits cap older bedrock formations that are located below the water table. Groundwater flow is laterally driven through confined glaciofluvial sediments (Hoaglund et al. 2002).

The interpreted geologic and hydrogeologic framework suggests an important connection between regional aquifers and Lake Vättern that needs to be better explored. As Lake Vättern is an important drinking water resource for 250,000 people, further work is needed to constrain possible groundwater and nutrient fluxes through this system.

Conclusions

An in situ temperature profile from a 2-km borehole in southern Lake Vättern was used to identify a zone of groundwater flow in a 110 m thick Quaternary unit of glacial and glaciofluvial sediments deposited on top of the regional Visingö Group sandstones. At the drilling site, the glacial and glaciofluvial sediments through which the groundwater is flowing are confined by a thick pro- and postglacial sedimentary sequence. The infiltration of warmer fluids into the borehole, and laterally discontinuous nature of the Quaternary sediment cover towards the lake margins suggests that fluids are sourced from depth, and are migrating through fractures in the underlying sandstone unit.

Modelling shows that fluid velocity through the glacial and glaciofluvial sediments can be maintained by a moderate total head of 10–50 m over 1–10 km of transport through clean sand and gravel sediments. The modelled vertical velocities in the borehole and lateral transport velocities may be overestimated if the applied mean annual bottom water temperature of Lake Vättern is too low. This error could arise from gaps in the observational lake temperature dataset in December through March, and/or long-term warming of bottom waters during the past decade(s).

The study highlights a plausible geologic framework conducive to substantial groundwater flow into Lake Vättern (Fig. 13). Further work is needed to determine the exact transport paths and discharge areas to the lake and to assess the significance of groundwater discharge to its freshwater and nutrient balance.

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References

Anderson, M.P., 2005: Heat as a ground water tracer. Groundwater 43, 951–968. doi:10.1111/j.1745-6584.2005.00052.x.

Andréasson, P.-G. & Rodhe, A., 1990: Geology of the Protagine Zone south of Lake Vättern, southern Sweden: a reinterpretation. Geologiska Föreningens i Stockholm Förhandlingar 112, 107–125. doi:10.1080/11035899009453168.

Artemieva, I.M. & Mooney, W.D., 2001: Thermal thickness and evolution of Precambrian lithosphere: a global study. Journal of Geophysical Research 106(B8), 16,387–16,414. doi:10.1029/2000JB900439.

Axberg, S. & Waldstein, P., 1980: Distribution of the sedimentary bedrock in Lake Vättern, southern Sweden. Acta Universitatis Stockholmiensis 34, 15–26.

Bense, V.F., Gleeson, T., Loveless, S.E., Bour, O., & Scibek, J., 2013: Fault zone hydrogeology. Earth-Science Reviews 127, 171–192. doi:10.1016/j.earscirev.2013.09.008.

Bense, V.F., Person, M.A., Chaudhary, K., You, Y., Cremer, N., & Simon, S., 2008: Thermal anomalies indicate preferential flow along faults in unconsolidated sedimentary aquifers. Geophysical Research Letters 35 (24), L24406. doi:10.1029/2008GL036017.

Bingen, B., Nordgulen, Ø., & Viola, G., 2008: A four phase model for the Sveconorwegian orogeny, SW Scandinavia. Norwegian Journal of Geology 88, 43–72.
Sedimentary formations for geothermal exploration. Geothermics 58, 49–61. doi:10.1016/j.geothermics.2015.08.004.

Sundberg, J., Näslund, J.-O., Wrafter, J., O’Regan, M., Jakobsson, M., Preto, P., & Larson, S.Å., 2017. Thermal data for paleoclimate calculations from boreholes at Lake Vättern, south-central Sweden. SKB report P-16-03, Svensk Kärnbränslehantering, Stockholm. ISSN 1651-4416.

Swärd, H., O’Regan, M., Ampel, L., Ananyev, R., Chernykh, D., Flodén, T., Greenwood, S.L., Kylander, M., Mört, C.M., Preto, P., & Jakobsson, M., 2016: Regional deglaciation and postglacial lake development as reflected in a 74m sedimentary record from Lake Vättern, southern Sweden. GFF 138. doi:10.1080/11035897.2015.1055510.

Swärd, H., O’Regan, M., Björck, S., Greenwood, S., Kylander, M., Mört, C.-M., Pearce, C., & Jakobsson, M., 2018: A chronology of environmental changes in the Lake Vättern basin from deglaciation to its final isolation. Boreas 47(2), 609–624. doi:10.1111/bor.12288.

Vidal, G., 1976: Late pre cambrian microfossils from the Visingsö Beds in southern Sweden. Fossils and Strata 9, 57.

Vidal, G., 1984: Lake Vättern. Geologiska Föreningen i Stockholm Förhandlingar 106, 397. doi:10.1080/11035898509454682.

Wik, N.-G., Andersson, J., Bergström, U., Claeson, D., Juhojuntti, N., Kero, L., Lundqvist, L., Möller, C., Sukotjo, S., & Wikman, H., 2006: Beskrivning till regional berggrundskarta über Jönköpings län. Sveriges Geologiska Undersökning K 61, 60.

Wohlfarth, B., Björck, S., Funder, S., Houmark-Nielsen, M., Ingolfsson, O., Lunka, J.P., Mangerud, J., Saarnisto, M., & Vorren, T., 2008: Quaternary of Norden. Episodes 31(1), 73–81.